

## Tests of neodymium content in selected materials

Published online: 06-07-2020

**Paweł Friebe**

KOMAG Institute of Mining Technology, Pszczyńska 37, 44-101 Gliwice, Poland

e-mail: pfriebe@komag.eu

Keywords: rare earth elements, REE, mechanical processing, separation, new technologies

Słowa kluczowe: pierwiastki ziem rzadkich, REE, przeróbka mechaniczna, separacja, nowe technologie

Abstract:

Rare earth elements are recognized as Critical Raw Materials (CRMs) due to their wide range of applications in the glass, steel, chemical and electronic industries. Often rare earth elements are referred to as a single group, but in practice each element has individual technical applications. Therefore, the demand varies for each element. Demand for rare earth elements is likely to increase in the future due to use of NdFeB magnets, especially in vehicles with electric motors and wind turbines. This publication presents research results aimed at finding raw material or waste that can be used to obtain neodymium at economical profit. This publication presents tests aimed at an identification of the raw material from which neodymium can be obtained. Research began with an identification of materials that could potentially become an economically viable source of neodymium extraction. The following materials were selected: natural aggregates, fine-grained raw materials of magma origin as well as coal sludge and fine-grained waste after hard coal enrichment. These raw materials were subject to content analysis by mass spectrometry, with ionization in inductively compressed plasma (ICP-MS).

Streszczenie:

Pierwiastki ziem rzadkich zostały uznane w ostatnich czasach jako surowce krytyczne ze względu na ich szeroki zakres zastosowań w przemysłach: szklarskim, stalowym, chemicznym i elektronicznym. Często pierwiastki ziem rzadkich łączone są w jedną grupę, jednakże w praktyce każdy pojedynczy pierwiastek posiada odrębne zastosowania, dlatego popyt na każdy pierwiastek jest inny. Prognozy wskazują na prawdopodobny wzrost zapotrzebowania na pierwiastki ziem rzadkich, co może być związane między innymi ze zwiększenia stosowania magnesów NdFeB, szczególnie w pojazdach hybrydowych i elektrycznych oraz turbinach wiatrowych. W niniejszej publikacji przedstawiono badania mające na celu zidentyfikowanie surowca, z którego będzie można pozyskać neodym. Badania rozpoczęto od wskazania materiałów, które potencjalnie mogą stać się ekonomicznie uzasadnionym źródłem pozyskiwania neodymu. Wytypowane zostały: kruszywa naturalne, drobnoziarniste surowce pochodzenia magmowego oraz muły węglowe i drobnoziarniste odpady po wzbogacaniu węgla kamiennego. Surowce te zostały poddane analizie zawartości neodymu metodą spektrometrii mas, z jonizacją w plazmie indukcyjnie sprężonej (ICP-MS).

### 1. Introduction

A big interest in rare earth elements (REE) results from their specific and required properties. They have a wide application in state-of-the-art technologies and industries: glass-making, steel, chemical and electronic. In recent years rare earth elements became an object of many research and development projects. A development of new technologies causes a systematic increase in the demand of these elements.

One of the key elements of rare earth, used in the industry, is neodymium. This element is used for a production of strongest permanent magnets, which are applied in electric motors of electric and hybrid cars, in some electric energy generators, hard disks and professional playing equipment.

Materials with a small neodymium content are used in lasers for generating laser beams of big power and in infrared spectrum. Besides, neodymium is used in the glass making industry, also for a production of hard disks, audio equipment as well as for conducting magnetic resonance. Due to a development of the latest technologies forecasts indicate a probable increase in demand of neodymium and of its price.

The biggest difficulty in obtaining rare earth elements is their small concentration in mineral resources. Present projects of the KOMAG Preparation systems Division, connected with the subject-matter of separating rare earth elements, are in the stage of searching appropriate materials. REE do not occur in the nature as pure elements. Most often they occur in a form of chemical compounds such as oxides, phosphates, silicates, carbonates and halides [1]. More than 250 minerals, among others such as e. g. allanite, apatite, bastnasite, xenotime or monazite, are known.

The content of rare earth elements in them, expressed as oxides, can reach even up to 70-74 % [2]. The chemical compounds and minerals, mentioned before, occur as mixes in many rocks such as: basalt, granite, gneiss, shale and silicate rocks.

At present Poland does not possess its own recognized raw materials resources which could constitute an economical source of obtaining REE. Their occurrence, in a form of poor deposits, is reduced to the region of Szklarska Poręba, the Sudeten Mountains, somewhere Białystok way and sand on the Baltic Sea beaches. The waste heaps from the phosphogypsum industry and ashes from the power plants burning and co-burning coal are rare earth elements. These wastes can be an essential source of regaining rare earth elements.

The objective of research work, undertaken by KOMAG, consisted in testing of selected groups of materials which, subject to proper separation process, will be a source of obtaining neodymium. The work in this scope included: obtaining of materials and their preparation for tests, tests of REE content using mass spectrometry which ionization in inductively compressed plasma (ICP-MS) and an analysis of obtained results.

Different materials were used for tests. The resources from sedimentary deposits were used: raw material from sand deposit, and fine-grained fall through the classifier sieves for washing aggregates. Besides, the test incorporated coal sludge and fine-grained waste after the coal enrichment. The resources from magma deposits: fine-grained granite aggregate and fine-grained basalt aggregate were used as well. In the further part of this article the most important sources of getting minerals, containing REE, are presented.

## 2. Sources of gaining rare earth elements

Neodymium, as well as other REE, do not occur in a pure form in the nature. It can only be found as a component of minerals, presented below. So far more than 250 minerals, containing REE, have been recognized, however at present an exploitation of deposits containing only some minerals, among others such as: bastnasite, monazite, xenotime and laterite clay (China) [1, 2] is economic in a commercial scale. Neodymium occurs in the earth's crust in the amount of 38 ppm [3].

The biggest producers of REE raw materials mainly exploit seams of three types of original ores: bastnasite (USA, China), monazite (Brazil, India, Malaysia, Sri Lanka, Thailand) and laterite clay (China). Besides, the REE are obtained as co-products during an exploitation of seams of xenotime or loparite ores as well as apatite and phosphorite ores (Russia), uranium ores (USA), iron ores (Bayan Obo, China) and ilmenite with monazite ores (Australia) [2].

Bastnasite is a fluorocarbonate of the chemical formula  $(Ce, La, Y)CO_3F$ . It occurs in pegmatites, granites and metamorphic rocks in the zones, where a contact metamorphism plays a dominating role [4]. The cerium element is replaced by lanthanum, yttrium or other light rare earth elements. Bastnasite usually co-occurs with other minerals such as allanite, fluocerite and others containing REE [5].

Monazite is a phosphate mineral of the chemical formula  $(Ce, La, Nd, Th)(PO_4)$ . It usually occurs in a form of grains of small sizes as an accessory mineral in magnetic rocks or metamorphic ores such as granite, pegmatite, basalt, shale and gneiss [6, 7, 8, 9]. Monazite grains are resistant to an impact of the atmosphere. Bed-rocks are subject to weathering and to erosion which cause a transport of monazite grains and their accumulation in valleys of rivers and streams. Accumulations of grains of a certain size form a chipping seam which can be exploited for obtaining heavy elements, including

rare earth elements and thorium [10]. A general chemical formula of monazite shows an exchangeability of cerium, lanthanum, neodymium and thorium in the mineral structure.

Deposits of laterite clay, containing rare earth elements, are generated in the result of weathering of magmatic rocks (usually granite), which contain compounds of rare earth elements. Due to weathering rocks are subject to a decomposition – among others a ionization of the compounds of rare earth elements occurs. Then the rare earth elements are adsorbed by clay minerals [11]. Laterite clays are a very important source of heavy rare earth elements (HREE). Due to their nature clays require a physical beneficiation only to a small extent or to no extent at all. They are directly processed with use of hydrometallurgical methods due to a big content of rare earth elements [12].

Xenotime is a phosphate mineral of a chemical formula  $YPO_4$  and of properties similar to monazite. The main features of xenotime are: high yttrium content (above 50%), low content of light rare earth elements (LREE), significantly lower content of thorium than monazite [13]. Xenotime is a rare mineral which similarly to monazite occurs as accessory mineral in veins of magmatic rocks. A process of creating chipping deposits of xenotime develops in convergence with monazite [14]. This mineral can contain radioactive elements such as uranium or thorium and the element such as tungsten. In some deposits the content of tungsten was detected [15].

Xenotime, monazite and bastnasite are minerals which can occur in the rocks such as granite, basalt, pegmatite and others mentioned above. The materials, used for tests, are characterized below.

Granite is an abyssal magmatic rock of evidently crystalline structure. The rock is generated due to a slow crystallization of magma under the Earth surface. The main minerals of granite are: orthoclase, plagioclase, quartz and biotite. The content of rare earth elements in this rock depends on the content of accessory minerals. A part of granite accessory minerals contains REE. They include among others: monazite, xenotime, allanite, titanite and anatase [16, 17].

Basalt is a basic, soiled outflow (volcanic) rock of very fine-grain structure (cryptocrystalline) or aphanite, sometimes porphyry. The main minerals of this rock are: pyroxenes, plagioclase, mica, amphibole. A presence of rare earth elements in basalt rocks is shown in many research projects [18, 19, 20]. The presence of rare earth elements also in these rocks is connected with the content of accessory minerals [21].

The presence of rare earth elements was detected not only in the rocks and minerals of magmatic origin, but also in coal and in the rocks accompanying coal. The Polish coal mining industry produces significant amounts of wastes, which are generated in the result of hard coal exploitation and preparation. Clay minerals are an original carrier of rare earth elements in coal and coal wastes [22, 23]. They are mainly sedimentary rocks occurring in roofs and floors as well as in interlayers of coal seams. The rocks, accompanying coal, are treated as waste in the hard coal beneficiation process. The following wastes can be distinguished:

- coarse-grained wastes e. g. from heavy-medium separators of grain sizes 200-20 mm,
- fine-grained wastes e. g. from jigs of grain sizes 20-0,5 mm,
- very-fine grained wastes e. g. from flotation beneficiation <1 mm.

Generated wastes contain vestigial elements including rare earth elements. A concentration of rare earth elements in the rocks, accompanying hard coal seams, depends on a number and kind of clay minerals due to their higher ability of ion exchange and sorptive properties [23]. The best sorptive properties have the minerals such as montmorillonite and illite [24] due to their structure and this is the reason why coal wastes, containing these minerals, will be a potentially better carrier of rare earth elements (REE).

A process of separating rare earth minerals embraces preparation processes with use of the devices characterized in the publication [25].

### 3. Rare earth elements on the market, demand and price of neodymium

Rare earth elements are more and more commonly used, in particular in high-tech industries, what has a significant impact on their price. Each branch of industry has different requirements as regards the purity, so they occur in different forms on the market. These elements are in a form of concentrates:

- bastnasite concentrate (60-85% REO – Rare Earth Ore, rare earth oxides),

- monazite concentrate (55-60% REO),
- xenotime concentrate (>25% REO),
- bastnasite-and-monazite concentrate (30%, 60% or 71% REO).

Apart from that these elements also occur on the market as processed raw materials, having a form of:

- mixed metal (98-99% of rare earth elements),
- ferrocerium (74% of mixed metal),
- individual elements of 96-99.9999% purity,
- compounds such as carbonates, chlorides, fluorides, nitrates and others [26].

Changes in demand and price of the most desirable rare earth elements on the market, together with a forecast for the years 2022 and 2025, are presented in Tables 1. and 2. Starting from the year 2015, a demand for presented elements increases continuously till the year 2025, but the biggest increase occurs in the case of neodymium and the lowest one – in the case of lanthanum and yttrium. As regards the price a continuous increase is achieved only by neodymium and the other elements experience increases and decreases of prices.

**Table 1.** Tabulation of demand of five most desirable rare earth elements on the market over the years 2015–2025 [27]

	Neodymium	Lanthanum	Cerium	Praseodymium	Yttrium
Years	[Mg]				
2015	11 647	11 578	8 114	4 342	2 810
2019	18 452 ↑ 58%	12 627 ↑ 9%	9 067 ↑ 12%	5 999 ↑ 38%	3 065 ↑ 9%
2022	21 620 ↑ 17%	13 476 ↑ 7%	9 677 ↑ 7%	6 716 ↑ 12%	3 271 ↑ 7%
2025	23 073 ↑ 7%	14 382 ↑ 7%	10 327 ↑ 7%	7 168 ↑ 7%	3 491 ↑ 7%

**Table 2.** Tabulation of five most desirable elements of purity min. 99% (yttrium min. 99.9999%) on the market over the years 2015–2025 [27]

	Neodymium	Lanthanum	Cerium	Praseodymium	Yttrium
Years	[USD/Mg]				[USD/kg]
2015	68 543	6 955	6 411	119 963	21
2019	108 786 ↑ 58%	7 033 ↑ 1%	4 197 ↓ 34%	119 103 ↓ 1%	41 ↑ 95%
2022	123 355 ↑ 13%	6 558 ↓ 7%	3 248 ↓ 22%	113 105 ↓ 5%	35 ↓ 14%
2025	148 444 ↑ 20%	6 932 ↑ 6%	3 308 ↑ 2%	119 093 ↑ 5%	38 ↑ 9%

A significant demand increase for neodymium as well as its price increase in comparison with previous years can be caused by a use increase of magnets made of neodymium, iron and boron alloy in the industry. Due to using these magnets in hybrid and electric cars their drives enable to achieve the highest possible efficiency and profitability. These magnets are also used in generators of very big off-shore wind turbines, reaching an increased efficiency in comparison with a conventional generator with a mechanical gear. Motors, using the above mentioned magnets which enable to achieve smaller dimensions and a smaller weight in comparison to the motors using ferrite magnets, are used in the aviation industry as well. Advantages, resulting from using rare earth elements in technology, contribute to their more and more frequent use in the industry, replacing other solutions.

#### 4. Tests of neodymium content in selected materials

Research work, undertaken at the KOMAG Institute, started from choosing materials which potentially can contain rare earth elements. The following materials were selected: material aggregates – sands, fine-grained raw materials of magmatic origin, coal silts and fine-grained wastes after hard coal beneficiation. The selected raw materials were subject to an analysis of the content using the mass spectrometry method with ionization in inductively compressed plasma (ICP-MS). The tests were directed towards a determination of neodymium element content.

##### 4.1. Testing material

The following materials were used for tests:

- Sand – Sand Mine 1

The Sand Mine 1 exploits a deposit, whose main mineral is back-filling sand and the accompanying mineral is a sand-and-gravel mix. The deposit is mined with use of a dredger excavator. Then the material is transported to the Preparation Plant, where it is subject to rinsing, classification and drying processes. Commercial products are: construction sands, rinsed and dried sands as well as gravels. The deposit is divided into two exploitative slopes having the material of different characteristics. One sample of raw material from each slope was taken. The sample material was taken by KOMAG employees.

- Sand – Mine 2

The Sand Mine 2 exploits a Quaternary deposit of a river origin. This mine conducts a deposit exploitation from under the water surface using a sucking dredger. Then the material is transported to the Preparation Plant using among others a wheel dewaterer, screens and a classifier. This Plant produces aggregate of the following sizing: 16-8 mm and 8-2 mm. The material, used for tests, is the material which passed through the bottom sieves (slot 2 mm) of the pulsatory classifier. A pulsatory classifier is a device, in which a separation of the material, according to density, takes place. The material is positioned in layers – at the top there are layers of the smallest density, and at the bottom-layers of biggest density. Therefore, if the feed to the device contains grains of minerals of big density (including minerals containing REE), these grains will leave the device through the bottom sieves. The material samples were taken by the Mine staff.

- Coal sludge – Hard Coal Mine 1

96% of commercial reserves of the Hard Coal Mine 1 contain coal of types: 34 and 35. The Preparation Plant beneficiates hard coal in grain classes 200-20 mm and 20-0 mm. The Plant technology includes a system of crushing and preclassification of raw coal to obtain the grain class 200-0 mm, which is then separated into grain classes 200-20 mm and 20-0 mm. In the successive step the class 200-20 mm is beneficiated in heavy medium separators and the class 20-0 mm is beneficiated gravitationally. Dewatering screens (class 200-20 mm) and dewatering centrifugal screens as well as dewatering screens (class 20-0 mm) are used for dewatering beneficiation products. Desludging of technological water is conducted with use of a radial concentrator. Coal sludge, used for tests, came from the radial concentrator. The material samples were taken by the Mine staff.

- Coal sludge – Hard Coal Mine 2

The Mine produces coal of type 31.2. The Preparation Plant beneficiates hard coal in grain classes 200-80 mm and 80-16 mm. The Plant technology includes a system of crushing and preclassification to obtain the grain class 200-0 mm. The obtained material, in the following step, is separated into grain classes 200-80 mm, 80-16 mm and 20-0 mm. Classes 200-80 mm and 80-16 mm are beneficiated in heavy medium separators, and class 20-0 mm is directed to mixes after screening class 6-0 mm. Technological water is clarified in a radial concentrator. Desludging of technological water takes place in radial concentrators. Dewatering of beneficiation and desludging products takes place in vibratory screens, dewatering centrifugal sieves, sedimentation centrifuges and filtration presses. Coal sludge, used for tests, comes from the radial concentrator. The material sample was taken by the Mine staff.

- Flotation waste – Hard Coal Mine 3

This Mine produces coal type 34.2 and steam coal. The Preparation Plant beneficiates hard coal in grain classes: 65-10 mm, 10-0 mm and 1-0 mm. The Plant technology includes crushing and preclassification system to obtain the grain class 65-0 mm. Then the material is subject to a classification for grain classes: 65-10 mm and class 10-0 mm. The grain class 65-10 mm is directed to a three-product gravitational beneficiation process and class 10-0 mm is a commercial product - steam coal. Middlings from the gravitational beneficiation process are subject to the crushing stage and to classification to the grain size 10-0 mm, and then secondarily it is gravitationally beneficiated. Desludging of technological water takes place in radial concentrators. Coal sludge, obtained from the radial concentrator, is directed to flotation machines where they are beneficiated. Dewatering of beneficiation products takes place on dewatering screens, in radial concentrators, centrifuges, centrifugal sieves and chamber presses. The flotation waste, used for tests, comes from the chamber press. The material sample was taken by the Mine staff.

- Flotation waste – Hard Coal Mine 4

This Mine produces hard coal of type 35.1. The Preparation Plant beneficiates hard coal in grain classes: 150-20 mm, 20-0 mm and 0.315-0 mm. The Plant technology includes the preclassification system to the grain sizes 150-0 mm. Then the material is subjected to the classification for grain classes: 150-20 mm and 20-0 mm. The grain class 150-20 mm is directed to a beneficiation in heavy medium, and class 20-0 mm is beneficiated gravitationally. Desludging of technological water takes place in radial concentrators. In the next step flotation beneficiation of coal sludge in the scope of grain size 0.315-0 mm is conducted. Dewatering of beneficiation products takes place on vibratory screens, in bucket conveyors, radial concentrators and filtrating presses. The flotation waste, used for tests, comes from the filtrating press. The material sample was collected by the Mine staff.

- Fine-grained basalt aggregate 2-0 mm – Basalt Mine 1

This Mine produces basalt aggregates of many graining sizes. The Mine deposit is exploited with use of drilling-and-blasting technology. The technology includes multi-stage crushing and classification. Fine-grained basalt aggregate 2-0 mm, used for tests, was taken by the Mine staff.

- Fine-grained basalt aggregate – Basalt Mine 2

This Mine produces basalt aggregates of many types of graining. The technology includes multi-stage crushing and classification. Fine-grained basalt aggregate 2-0 mm, used for tests, was taken by the Mine staff.

- Fine-grained granite aggregate 2-0 mm – Granite Mine 1

This Mine produces granite aggregates of many types of graining. The technology includes multi-stage crushing and classification. Fine-grained granite aggregate 2-0 mm, used for tests, was taken by the Mine staff.

## 4.2. Preparation of materials

This stage was oriented onto obtaining representative samples of sands, coal sludges, flotation wastes, fine-grained granite and basalt aggregates of 1 kg weight. The weight of samples was determined by the KOMAG Laboratory of Material Engineering and Environment. Standard tools of the Minerals Processing Laboratory were used for a preparation of samples.

The samples of sand, granite and basalt were separated with use of the Jones's splitter. Each material sample weighed 1 kg. The samples were put into a string bag and then they were delivered to the laboratory.

Flotation wastes as well as coal sludges are materials of big humidity. They were placed in plastic cuvettes; samples, which were used for a determination of the REE content in raw material, were separated from each sludge and flotation waste. The materials were dried in the laboratory drier, which caused a strong conglomeration of fine grains of flotation wastes and sludges into thick agglomerates,

which afterwards were comminuted in disk mill adjusted for the smallest distance between the mill disks.

In the following step the second part of samples of flotation wastes and coal sludges was separated. It served for testing the REE content in the ash which was left after burning these materials. Similarly to the previous case, the materials were placed in cuvettes, from which the samples were separated and then they were dried in the laboratory drier and ground in the disk mill. The Standard PN-ISO 1171:2002 – Solid fuels – Determination of ash was used in the process of obtaining ash. The laboratory muffle furnace was used for burning materials. According to the Standard mentioned above 1-2 g of material were prepared for a crucible, in total:

- Hard Coal Mine 1 – about 20 g of coal sludge,
- Hard Coal Mine 2 – about 24 g of coal sludge,
- Hard Coal Mine 3 – about 23 g of flotation wastes,
- Hard Coal Mine 4 – about 22 g of flotation wastes.

The furnace was heated to the temperature of 500°C within 60 minutes and this temperature was kept for 30 minutes. After that time period, within the following 50 minutes the temperature inside the furnace was increased to 815°C. In this temperature the samples were heated for 60 minutes. Then they cooled down for a few hours. Cool samples were placed in the exsiccator. After weighing the samples on the analytical scales the following results were obtained:

- Hard Coal Mine 1 – about 6 g of ash,
- Hard Coal Mine 2 – about 11 g of ash,
- Hard Coal Mine 3 – about 15 g of ash,
- Hard Coal Mine 4 – about 18 g of ash.

The testing material, prepared in such a way, was conveyed to the KOMAG Laboratory of Material Engineering and Environment.

#### 4.3. Tests of rare earth elements' contents

Tests of REE contents were conducted in the way presented below. Laboratory samples of sand, coal sludges, flotation wastes and ashes were tested from the point of view of dry mass. Their mineralization was also conducted. The samples were mineralized in the closed-loop dry system, using the microwave mineralizer. The quality of pulping the samples under testing was subject to a visual assessment. In the result of such an approach a colourless and clean solution was obtained for the majority of the samples. Tests of neodymium content were conducted with use of mass spectrometry, with ionization inductively coupled plasma (ICP-MS). The results of tests are presented in Tables 3, 4 and 5.

**Table 3.** Tabulation of neodymium content in aggregates

Identification of samples		Nd content [ppm]
Sand Mine 1, top slope of deposit	Sand	<5
Sand Mine 1, bottom slope of deposit	Sand	<5
Sand Mine 2	Sand	<5
Basalt Mine 1	Fine-granulated basalt aggregate	38.2
Basalt Mine 2	Fine-granulated basalt aggregate	21.7
Granite Mine 3	Fine-granulated granite aggregate	13.5

**Table 4.** Tabulation of neodymium content in coal sludge and ashes after burning the sludge

Identification of samples		Nd content [ppm]
Hard Coal Mine 1	Coal sludge	6.5
	Ash after burning sludge	33.5
Hard Coal Mine 1	Coal sludge	11.3
	Ash after burning sludge	13.8

**Table 5.** Tabulation of neodymium content in coal wastes and ashes after burning the waste

Identification of samples		Nd content [ppm]
Hard Coal Mine 1	Wastes from flotation beneficiation of coal	<5
	Ash after burning flotation wastes	15.2
Hard Coal Mine 1	Wastes from flotation beneficiation of coal	7.0
	Ash after burning flotation wastes	24.0

## 5. Summary and direction of further research work

Tests of the material taken from the top slope and from the bottom slope of the deposit in the Sand Mine 1 showed the contents of neodymium < 5 ppm. Similarly, the mineral taken from the bottom sieves of the classifier (fallen through) in the Sand Mine 2 contained <5 ppm of neodymium. The highest amount of the neodymium element, among fine-granulated basalt aggregates contained <5 ppm of neodymium.

The highest amount of the neodymium element, among fine-granulated basalt aggregates contained the aggregate from Basalt Mine 1 – 38.3 ppm. This content is comparable with the average content of this element in the earth's crust. The material from the Basalt Mine 2 contained 21.7 ppm. Coal sludge from the Hard Coal Mine 1 contained 6.5 ppm of neodymium. The burning process of the material led to a multiple increase of the element content, to the amount of 33.5 ppm. The content of neodymium in the coal sludge from the Hard Coal Mine 2 before its burning was 11.3 ppm and after burning – 13.8 ppm. Before burning the sludge from the Hard Coal Mine 1 was characterized by a higher neodymium content, among coal sludges, and after burning the bigger content was reached by the Hard Coal Mine 2. Therefore it can be stated that a searched element content increased by 415% in the case of the material from the Hard Coal Mine 1 and by 22% – in the case of the material from the Hard Coal Mine 2.

An analysis of the neodymium content in the waste from the flotation process, before burning, from the Hard Coal Mine 3 gave the result <5 ppm. Burning of this material caused an increase in the neodymium content in the flotation waste from the Hard Coal Mine 4, before burning, it was 7.0 ppm and after burning – 24.0 ppm. The material from the Hard Coal Mine 4 is characterized by a bigger neodymium content both before burning as well as after burning. An increase by 242% of the searched element content in the wastes of the Hard Coal Mine 4 was observed.

The conducted tests enabled to draw a series of conclusions concerning a usability of the tested materials for gaining one of the rare earth elements- neodymium. The obtained results, concerning the

neodymium content in sand deposits can indicate lack of the searched element in the material. Therefore, these materials are not useful for gaining neodymium. The determined neodymium contents in granite and basalt aggregates enabled to conclude that these materials contain neodymium compounds in small quantities, up to 38.2 ppm. A separation method, chosen correctly, will enable to increase the neodymium content in the obtained product. Basing on the obtained results of the tested element content in coal sludges and flotation wastes, it can be stated that the neodymium compounds occur in them in very small quantities, up to 11.3 ppm. An incineration of coal sludges and flotation wastes led to a concentration increase (e. g. from 6.5 ppm to 33.5 ppm). At present it cannot be excluded that a part of the particles, containing neodymium, is lost irretrievably. A loss of a part of these particles can happen during their burning, during their transport together with escaping gases. These gases are collected through the exhaust hole in the muffle furnace. In the future a method, enabling to exclude or confirm such a phenomenon, will be elaborated.

Future research work will include further analyses of the materials used in this work as well. It is planned to conduct analyses of granulometric contents of granite and basalt aggregates. An application of the sieves, having the following mesh sizes: 2 mm, 1 mm, 0.5 mm, 0.25 mm, 0.125 mm and 0.063 mm, will enable to gain narrow grain classes. As it can be concluded from the information presented in the literature, it is expected to obtain a higher REE concentration in the finest-grained classes. Then tests of rare earth elements contents in the obtained grain classes will be conducted. These tests are indispensable for a rejection of these grain classes which have a small REE content at the very beginning, before this material is directed to the separation process.

## References

- [1] Gupta C. K., Krishnamurthy N.: *Extractive Metallurgy of Rare Earths*, CRC Press, Florida, 2005.
- [2] Jordens A., Cheng Y., Waters K., *A review of the beneficiation of rare earth element bearing minerals*, Minerals Engineering, 2013.
- [3] <https://environmentalchemistry.com/yogi/periodic/Nd.html>, [accessed: 12.02.2020].
- [4] Turlin F., André-Mayer A., Moukhsil A., Vanderhaeghe O., Gervais F.: *Unusual LREE-rich, peraluminous, monazite- or allanite-bearing pegmatitic granite in the central Grenville Province, Québec*. Ore Geology Reviews, Elsevier, 2017.
- [5] Encyclopaedia Britannica, <https://www.britannica.com/science/bastnaesite> [accessed: 09.10.2019].
- [6] Broska I., Kubiš M., Williams C., Konečný P.: *The compositions of rock-forming and accessory minerals from the Gemic granites*, Bulletin of the Czech Geological Survey, 2002.
- [7] René M.: *REE and Y Mineralogy of the Krudum Granite Body*, Minerals, 2018.
- [8] Mckeough M., Lentz D, Mcfarlane Ch., Brown J.: *Geology and evolution of pegmatite-hosted U–Th ± REE–Y–Nb mineralization, Kulyk, Eagle, and Karin Lakes region, Wollaston Domain, northern Saskatchewan, Canada: examples of the dual role of extreme fractionation and hybridization processes*, Journal of Geosciences, 2013.
- [9] Overstreet W.: *The Geologic Occurrence Of Monazite*, 1967.
- [10] <https://geology.com/minerals/monazite.shtml> [accessed: 30.03.2019].
- [11] Gupta C.K., Krishnamurthy N.: *Extractive metallurgy of rare earths*. International Materials Reviews 37 (5), 1992.
- [12] Yaraghi A., Ariffin K., Baharun N., *A Short Review on REE Recovery from Ion-Adsorption Clay, Aspects in Mining and Mineral Science*, 2019.
- [13] [http://nevada-outback-gems.com/mineral\\_information/Xenotime\\_mineral\\_info.htm](http://nevada-outback-gems.com/mineral_information/Xenotime_mineral_info.htm) [accessed: 19.06.2019].
- [14] Jamil H., Umor M. R.: *Heavy mineral distribution in stream sediment of tapah Area, Perak, Malaysia*, 2013.
- [15] Verplanck P., Hitzman M., *Rare Earth and Critical Elements in Ore Deposits, Reviews in Economic Geology* 18, 2016.
- [16] Ghaffar A.: *Enrichment of rare earth and radioactive elements concentration in accessory phases from*

- alkaline granite, South Sinai- Egypt, Journal of African Earth Sciences, Volume 147, Pages 393-401, November 2018.
- [17] Tanaka T.: Geological significance of rare earth elements in Japanese geosynclinal basalts, Contributions to Mineralogy and Petrology, 1975.
- [18] Frey F., Haskin M., Poetz J., Haskin L.: Rare Earth abundances in some basic rocks, Journal of Geophysical Research, 1968.
- [19] Zhang Y., Yu K., Qian H.: 4LA-ICP-MS Analysis of Clinopyroxenes in Basaltic Pyroclastic Rocks from the Xisha Islands, Northwestern South China Sea, Mineral- Open Acces Journal, 2018.
- [20] Sanematsu K., Moriyama T., Sotouky L., Watanabe Y.: Mobility of Rare Earth Elements in Basalt-Derived Laterite at the Bolaven Plateau, Southern Laos, 2011.
- [21] Adamczyk Z., Białecka B., Całus-Moszko J., Komorek J., Lewandowska M.: Rare earth elements of Orzeskie beds of south-west part Upper Silesian Coal Basin (Poland), 2015.
- [22] Całus-Moszko J., Białecka B.: Analiza możliwości pozyskania pierwiastków ziem rzadkich z węgla kamiennych i popiołów lotnych z elektrowni, Gospodarka Surowcami Mineralnymi, 2013.
- [23] Nowak J., Kokowska-Pawłowska M.: Zmiany koncentracji wybranych pierwiastków ziem rzadkich (REEs) w odpadach węglowych, Arch. Min. Sci. 62, 2017.
- [24] Stoch L.: Minerale ilaste, Wydawnictwo Geologiczne 1974.
- [25] Friebe P.: Separacja minerałów zawierających pierwiastki ziem rzadkich. KOMEKO 2019, Innowacyjne i przyjazne dla środowiska techniki i technologie przeróbki surowców mineralnych. Bezpieczeństwo - Jakość - Efektywność, Instytut Techniki Górniczej KOMAG, Gliwice 2019.
- [26] K. Podbiera-Matysik, K. Gorazda, Z. Wzorek, Kierunki zastosowania i pozyskiwania metali ziem rzadkich, Chemia Czasopismo Techniczne, 2012
- [27] Hykawy J., Chudnovsky T.: Industry Report – Rare Earths <http://static.squarespace.com/static/535e7e2de4b088f0b623c597/t/54697223e4b054b6f26537f7/1416196643789/Stormcrow-Rare+Earths+Industry+Report-Nov2014.pdf> [accessed: 17.02.2020].